LA-UR 80-3044

MASTER

TITLE: THE PIGMI TECHNOLOGY

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SUBMITTED TO: MARIA Workshop, University of Edmonton, Alberta, Canada, Oct. 20-24, 1980

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Form No. 836 R3
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UNITED STATES
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CONTRACT W-7405-ENG. 36

THE PIGMI TECHNOLOGY*

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I. INTRODUCTION

The accelerator technologies relevant to the design of a medically practical pion generator for medical irradiations (PIGMI) have been identified and developed under the PIGMI program of the Los Alamos Scientific Laboratory (LASL). The major technological innovations promoted by the PIGMI program are listed in Fig. 1. A "base-case" design for PIGMI is presented in this paper. Figure 2 shows a typical layout for this basic configuration in the proximity of a major medical center. More details on this base-case design and several alternative configurations will be described in a more complete PIGMI design report currently in preparation by the PIGMI design team. This design report will include a detailed cost breakdown that is expected to indicate a cost for the accelerator portion of the facility of about \$10 million, a cost for the treatment facility of about \$10 million, and a cost of approximately \$5 million for site preparation, giving a total cost of a PIGMI facility of about \$25 million.

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*This work was supported by the National Cancer Institute, Division of Research and Centers, Department of Health, Education, and Welfare.

II. ACCELERATOR SYSTEMS - GENERAL DESCRIPTION

A. Summary

The accelerator portion of the PIGMI facility consists of an injector, a radio frequency quadrupole (RFQ) linac structure, a drift-tube linac (DTL) structure, a coupled-cavity linac (CCL) structure, a 440-MHz rf system, six 1320-MHz rf systems, and a control and instrumentation system, as shown in Fig. 3. All of these components have been under development in the PIGMI program at LASL. The accelerator is 134 m long and is suitable for installation underground in a tunnel of modest cross section.

The 440-MHz RFQ linac dramatically simplifies the front end of the accelerator. It can accept a proton beam with an energy of only 30 keV, and bunch and accelerate it to an energy of 2.5 MeV in approximately 1.8 m, where the beam is ideally suited for injection into the DTL. The RFQ does this essential task better than any other known structure. It eliminates the need for a large and costly Cockcroft-Walton power supply, a complex multicavity buncher system, a low-energy beam transport system, and the associated control and instrumentation. The average accelerating gradient of the RFQ is about 1.4 MeV/m.

The DTL is a 440-MHz, single-cavity, post-coupled linac structure, approximately 30 m long, that accelerates the beam from 2.5 MeV to 125 MeV. It contains 150 drift tubes, each of which contain a small, permanent-magnet, quadrupole lens to focus the beam. The DTL is driven by a single klystron, which is coupled to the structure through an iris near the center of the DTL. The average axial electric field gradient is 6 MeV/m.

The CCL is a 1320-MHz structure of the "disk and washer" type that accelerates the beam from 125 MeV to 650 MeV in approximately 100 m. The structure is comprised of 108 tanks of 11 cells each, with the cell geometry of each tank optimized for the energy range that it spans. The entire structure is coupled together by 107 single-cell coaxial bridge couplers into a single resonant unit. Each bridge coupler contains a permanent-magnet quadrupole singlet to focus the beam. The entire CCL is driven by six klystrons that are coupled to the CCL through six bridge couplers symmetrically located along the structure. The average axial electric field gradient is 8 MeV/m.

A very attractive feature of the PIGMI accelerator is its stark simplicity. There are only two resonant units, one at 440 MHz, and one at 1320 MHz, which implies that there are only three principal setpoints in the control of the rf fields; namely, the amplitude of each and their relative phase. All magnetic quadrupoles (except those in the transition region between the DTL and CCL) are of the permanent magnet type, which requires no power supplies or associated instrumentation. The injection voltage is supplied by a rack-mounted 30 kV power supply. The low-energy beam transport system consists of a single einzel lens for control of the focusing and minimal steering for correction of any misalignments. In all, there are very few power supplies and very few active control parameters.

A modest, distributed, MULTIBUS-based control system, of the type being developed for other projects at FERMILAB, LASL, and NBS, can handle the control and diagnostic requirements of this facility. It is entirely practical to realize a three-state control; namely, OFF, STANDBY, and ON.

B. Injector System

The injector system has traditionally been an expensive and complicated component of a proton linac. The conventional injection energy of about 750 keV was reduced to 250 keV by the alternating phase focused (APF) structure in the PIGMI Prototype, further reduced to 100 keV in the RFQ proof-of-principal (POP) experiment, and finally reduced to 30 keV for PIGMI. Injector operation at 30 kV dramatically simplifies the design, allowing the ion source and associated electronics to be enclosed in a small vacuum housing and a single equipment cabinet, as shown in Fig. 4.

The 30-keV injection energy satisfies the RFQ requirement for efficient bunching in a minimum distance and the requirement for reliable operation of the single-gap high-brightness extraction system. Because of this low energy, electrostatic focusing of the ion beam is more effective than the magnetic focusing employed in the PIGMI Prototype. A three-element unipotential einzel lens was designed to provide this electrostatic focusing; the calculated beam profile for a 32-mA proton beam extracted from the ion source and transported through this system is shown in Fig. 5.

The einzel lens was selected because of the simplicity of fabrication, the minimal space requirement, and the lack of the power and cooling required by magnetic focusing. The excitation of this lens can be derived from a high-voltage divider system on the injector power supply. Calculations of this lens and extraction system have shown that ion currents in the range of 20-35 mA can be focused into the RFQ with a lens voltage in the range of 20-30 kV. Below 20 mA of extracted beam current, the divergence of the beam is too large for all of the beam to enter the einzel lens aperture, although most of the beam entering the einzel lens is focused into the RFQ.

C. RFQ Linac

The RFQ represents a revolutionary new focusing, bunching, and accelerating structure that promises to be an important part of many future proton, light ion and heavy ion facilities. The first RFQ structure in the western world was tested in the PIGMI laboratory in February, 1980. These tests were highly successful, confirming the general properties of the RFQ structure and gave excellent agreement between the measured properties of the beam and the predicted performance. The tests also confirm that the RFQ operates in a stable manner that is remarkably insensitive to injection energy errors, rf excitation errors, and structural fabrication errors.

The RFQ is considered by many to be the "missing link" in linac technology. It represents a superb answer to one of the last remaining questions of how to build simple, reliable and inexpensive proton or ion linacs. The RFQ offers the lowest injection energy of any known linac structure, it is the best buncher that has ever been conceived, and it bunches and accelerates the beam with less emittance growth than any other known system. It represents the best transformation that has ever been seen between the continuous beams that come from ion sources and the bunched and accelerated beams required by conventional linacs.

The RFQ eliminates the need for large and costly Cockcroft-Walton power supplies, complex multicavity buncher systems, low-energy beam transport systems, and the associated control and instrumentation.

The RFQ is essentially a vane-loaded cylinder as shown in Fig. 6, excited in a modified TE_{210} cavity mode, which produces a strong electric quadrupole field in the vicinity of the axis. The transverse components of this field, which are uniform in space and alternating in time, give rise to strong, alternating-gradient, focusing effects that can be used to focus beams of particles traveling along the axis of the structure. By scalloping the vane-tip geometry as shown in Fig. 6, a longitudinal component is introduced into the rf electric field in the vicinity of the axis, which can be used to bunch and accelerate the beams. Thus, the RFQ structure is capable of focusing, bunching, and accelerating beams of charge particles.

The structure is so simple that, for the first time, it is possible to configure the linac for adiabatic capture of continuous beams at low energy. This is done by introducing the scallops gradually so that the structure acts primarily as a buncher at the beginning, transforming gradually to an accelerator at the end. A computer-generated picture of such a vane tip is shown in Fig. 7. A cutaway view of the RFQ structure is shown in Fig. 8.

The RFQ is comprised of four regions; the radial matching section, the shaper, the gentle buncher, and the accelerating section. In the radial matching region, the vane aperture is tapered to adjust the focusing strength from almost zero to its full value in a very short distance; this allows the dc injected beam to be matched into the time-dependent focusing. In the next two regions, the shaper and the gentle buncher, the beam is adiabatically bunched as it is accelerated. At the end of the gentle buncher, the synchronous phase angle of the beam reaches its final value and the bunched beam is then accelerated in the final region. In this region, the vane radius, vane modulation, and phase angle are held constant to obtain the maximum possible acceleration gradient.

The PIGMI RFQ was designed and analyzed with the aid of the RFQ linac design and simulation code, PARMTEQ. The operating frequency is 440 MHz. It is designed to accept a 30-keV proton beam from the ion source and to focus, bunch, and accelerate the beam to an energy of 2.5 MeV in a length of 1.8 m. Each vane tip has a total of 200 scallops, varying in length from 0.27 cm at the beginning to 2.47 cm at the end. The minimum radial aperture of the structure is 1.9 mm.

The performance of this structure was analyzed in detail with the PARMTEQ code. It captures 92% of a 30-mA beam to yield the PIGMI design current of 28 mA. The size, phase, and energy profiles of the beam are shown in Fig. 9. The normalized emittance [(area/π)$\cdot\beta\gamma$] of the input beam was taken to be 0.048 π cm$\cdot$mrad. The input and output phase spaces of the beam are shown in Fig. 10. The transverse emittance growth (for the 90% contour) is about a factor of 1.4, which is better than can be achieved by any other buncher/linac combination.

A coaxial manifold has been developed that provides a symmetrical, multislot driving arrangement for the RFQ cavity. A coaxial cavity, surrounding the RFQ cavity, is excited in a coaxial TEM mode. The magnetic fields in the TEM mode are orthogonal to the magnetic fields in the RFQ mode. These fields can be coupled by diagonal slots, where the slot angles are determined by the magnitude and direction of the magnetic fields in the vicinity of the slots. Techniques are under investigation for resonating these slots so as to provide resonant coupling between the RFQ manifold and the RFQ cavity.

A technique has been proposed for coupling the RFQ manifold to the DTL so that the RFQ can derive its rf power from the DTL, thereby eliminating the necessity for a separate rf power source and drive line for the RFQ. This technique is being developed, and will be tested in the PIGMI laboratory in 1981.

D. DTL

The vast majority of the proton linacs are of the drift-tube linac type. Most of the linacs designed in the last ten years employ post couplers, developed at LASL by the principal investigators of the PIGMI program, to stabilize the distribution of the electromagnetic fields within the structure. The properties and performance of these structures are well known.

The PIGMI DTL differs from conventional DTLs primarily in scale, being more than twice the frequency, and hence, less than half the cross-sectional diameter of conventional linacs. The higher frequency and the low-duty factor of PIGMI make the optimum accelerating gradient of PIGMI higher than normal for conventional linacs, thus making the PIGMI facility significantly shorter.

The small size of the PIGMI DTL precludes normal fabrication and assembly techniques, which require entry of personnel into the interior of the structure for assembly and alignment. The PIGMI scheme is based on the preassembly of short (2.5-m) linac tank sections, into which the drift tubes can be introduced from the ends or through slots in the top into precision-bored holes along the bottom of the tank sections.

The PIGMI drift tubes are also considerably smaller than those in conventional DTLs, precluding the use of electromagnetic quadrupole lenses for focusing the beam. The PIGMI solution is to use permanent-magnet quadrupole lenses, made of modern materials in the best geometrical configuration (shown in Fig. 11), which results in very compact magnetic lenses of sufficient strength. The design is further simplified by allowing all of the quadrupoles to have a common length and strength throughout the structure.

The PIGMI DTL is conceived as a single-tank, post-coupled drift-tube linac that is approximately 30 m long and 0.4 m in diameter. The DTL operates at 440 MHz, the same as that of the RFQ, and accelerates the proton beam from 2.5 MeV to 125 MeV, with an average axial electric field of 6 MV/m. The peak power dissipation in the structure is 14.2 MW and the peak beam power is 3.4 MW for a total peak power requirement of 17.6 MW. The average power dissipated in the structure is only 51 kW or 1.7 kW/m.

The DTL structure has 150 drift tubes and 74 post couplers. All drift tubes have a 6-cm o.d., a 1-cm-diam bore hole, and are supported on a single stem from the bottom of the tank. Figure 12 shows a cutaway view of a portion of the DTL structure.

Each drift tube contains a permanent-magnet quadrupole lens to focus the beam. All 150 quadrupole magnets are identical in size and strength. They are made of samarium cobalt and are magnetized to produce a quadrupole gradient of 20 kG/cm over the 1-cm-diam bore.

The DTL structure is designed and analyzed with the aid of the linac design and simulation code, PARMILA. The structure accepts essentially 100% of the accelerated beam from the RFQ and accelerates it to 125 MeV. Figure 13 shows the size, phase, and energy profiles of the beam and Fig. 14 shows the input and output phase spaces. The beam suffers essentially no emittance growth in the DTL.

The 30-m linac structure is fabricated as twelve tank sections, each about 2.5 m long. The ends of the tank sections are located at points corresponding to the midplane of a drift-tube gap. The length, number of drift tubes, and maximum energy associated to each of the tank sections is given in Table I. The general mechanical feature of the first and last tank sections are shown in Fig. 15.

The tank sections are stiffened along the bottom by a structural member that supports the drift tubes. The drift tube mounting holes are precision bored through this structural member and tank wall. Post coupler mounting holes are bored along the side of the tank at locations corresponding to the midplane of every other drift tube and alternating from side-to-side of the structure. Each tank section has two half-meter-long slots in the top surface for access to the interior and for mounting vacuum pumps, fixed tuners, variable tuners, etc.

Before assembly of the entire structure, each tank section is fully assembled, complete with drift tubes, post couplers, tuners, monitor loops, etc. The drift tubes are aligned with the centers of the end flanges. The tank sections can be terminated by a conducting plane at each end, and the fine tuning on the resonant frequency and the adjustment of the post couplers can be done.

For final assembly, the tank sections are joined together, and supported by their end flanges, which are aligned to lie along a straight line. The end flanges are supported directly from the floor by support structures that have good transverse rigidity and poor longitudinal rigidity. The center of the DTL structure is anchored to a rigid longitudinal support.

E. Coupled-Cavity Linac

Significant discoveries made at LASL during the development of LAMPF in the 1960s, led the way to the development of practical coupled-cavity linac structures for acceleration of protons at energies in excess of 200 MeV. The major advance made at that time was the recognition of the importance of using biperiodic standing-wave structures excited in the $\pi/2$ cavity mode. The structure, developed at that time, is called the side-coupled structure and, when properly tuned, offers high efficiency in the conversion of rf power to beam power with exceptional stability in the distribution of the accelerating fields, a feature that is essential for reliable operation.

The Russians, in their interest in building a LAMPF-type machine, considered the LAMPF side-coupled structure and two other structures; namely, the ring-coupled structure, and a DAW structure. They selected the latter because of its large intercavity coupling constant and its potential for simple fabrication.

At the outset of the PIGMI program, it was assumed that the "high-beta" portion of PIGMI would utilize a scaled-down version of the LAMPF side-coupled structure. The only developments envisioned were ways to increase the intercavity coupling and ways to simplify the fabrication. It was quickly realized that the outstanding properties of the DAW structure satisfied both goals. A cutaway view of the DAW structure is shown in Fig. 16.

SUPERFISH, a powerful rf cavity calculational program developed at LASL, partly in response to the needs of the PIGMI program, was used to analyze the DAW structure in detail. Exhaustive computer studies with this program, coupled with test cavity experiments, led to a thorough understanding of the performance of this structure and to an optimized set of parameters for the PIGMI application.

In long linac structures, such as PIGMI, there is a need to break the structure into shorter sections to allow introduction of auxiliary apparatus such as beam focusing quadrupoles, beam diagnostic equipment, vacuum isolation valves, etc. In many cases, it is also desirable to couple these sections into longer resonant units to reduce the required number of rf power drive points and to lock the relative phase and amplitude of the fields in adjacent sections. To take optimum advantage of the superior properties of this structure, any required rf couplers should also be of the resonantly coupled type with large coupling constants, and for the practical reasons of structure tuning, the rf coupling of the linac structures should represent a minimum distortion of the field patterns in either element. Such couplers at LAMPF have been called "bridge couplers" because they bridge the resonant properties of the linac structure around the auxilliary apparatus.

Single-cell bridge couplers have been developed for the PIGMI application that are adequate to house the required apparatus within the linac structure. Figure 17 shows the general geometry of these bridge couplers for the values of β equal to 0.5, 0.6, 0.7, and 0.8 In the center of each bridge coupler there is a region of high magnetic field and zero electric field. Conducting radial supports in this plane have a negligible effect on the accelerating mode and a tolerable effect on the coupling mode. Hollow conducting radial supports provide suitable channels for the services required by the auxiliary apparatus housed within the bridge couplers, such as cooling water for the bridge coupler parts, signal leads for beam diagnostic devices, and control rods for mechanical devices. Practical designs for bridge couplers incorporating a variety of these features have been made.

The PIGMI CCL is approximately 100 m long and 0.34 m in diameter. The operating frequency is 1320 MHz, three times that of the DTL. It accelerates the proton beam from 125 MeV to 650 MeV with an average axial electric field of 8 MV/m. The peak power dissipation in the structure is 69 MW and the peak beam power is 14.6 MW for a total peak power requirement of 81.4 MW. The average power dissipated in the structure is only 250 kW, or about 2.5 kW/m.

The PIGMI CCL is comprised of 108 tanks of 11 cells each, whose lengths vary from 0.6 m to 1.0 m. The cell geometries are uniform throughout each tank, and differ from tank to tank. The tanks are resonantly coupled together by 107 single-cell bridge couplers, each containing a permanent magnet quadrupole singlet for focusing the beam. Figure 18 shows the geometry of the quadrupole singlet; all 107 quadrupole singlets are identical. They are made of a ceramic material magnetized to produce a quadrupole gradient of 5 kG/cm over the 2-cm-diam bore.The bore-hole diameter of the structure and of the bridge coupler is 2 cm.

The CCL structure is designed and analyzed with the aid of the linac design program, DAWDSN, and the linac simulation program, DAWLIN. The structure accepts essentially 100% of the accelerated beam from the DTL and accelerates it to 650 MeV. The size phase, and energy profiles for the beam are shown in Fig. 19. The input and output phase spaces of the beam are shown in Fig. 20. The beam suffers essentially no emittance growth in this portion of the PIGMI facility.

For the purpose of facility organization, the CCL is subdivided into 6 modules of 18 tanks each. A high degree of similarity is imposed on the organization of each module with regard to the distribution of the necessary auxiliary features such as rf drive points, beam and accelerator diagnostic instrumentation, and vacuum equipment. The center bridge coupler of each module accommodates one of the six 1320 MHz rf power systems. The end bridge coupler of each module is outfitted with a coaxial ceramic window and a compact beamline valve to provide vacuum isolation between modules for maintenance purposes. The remaining bridge couplers accommodate an array of vacuum pumps and diagnostic gear. Figure 21 shows a typical module, and Table II gives the length and maximum energy associated with each module.

Before the fabrication of each tank, the parts are assembled in a temporary fashion to check the resonant frequency and the stopband between the accelerating mode and the coupling mode. If changes are necessary, changes are made to the individual washers. When these constraints are satisfied, the fabrication of the tank is completed. The tanks are then joined together in small groups to test the properties of the bridge couplers; if minor changes are required in the bridge couplers, they can be made at this time. When the entire structure is assembled at its final destination, only minor tuning should be required to achieve the desired resonant frequency and field distribution.

F. RF Power Systems

The PIGMI frequencies of 440 MHz and 1320 MHz were chosen partly on beam dynamics considerations and partly on the availability of suitable klystrons. Many military radar klystrons have been designed to operate in the 400- to 450-MHz band and the next higher frequency band of 1250 to 1350 MHz. The PIGMI frequencies, which must be harmonically related, were chosen to fall in these ranges.

The costs of the rf systems were compared for three different beam-pulse patterns of a same duty factor; namely, 10-μs beam pulses at a 360-Hz repetition rate, 30-μs beam pulses at a 120-Hz repetition rate, and 60-μs beam pulses at a 60-Hz repetition rate. The shorter beam pulse and higher repetition rate reduce the cost of the pulse forming network (PFN) modulator, but consume more average power because of the larger number of cavity fill times. The longer beam pulse and lower repetition rate result in a 100-kW power savings over the medium pulse alternative and a 240-kW power savings over the short pulse alternative. The 60-μs, 60-Hz option has been adopted for PIGMI on the basis that the power savings resulting from the lower repetition rate will override the additional cost of the PFN modulators associated with the longer pulse length.

The cavity power dissipation for the 440-MHz portions of PIGMI (RFQ and DTL) are estimated to be 16.2 MW, and the beam loading for this same region corresponds to 3.5 MW. The rf pulse length must exceed the beam pulse length by the cavity fill time of approximately 15.6 μs. The rf duty factor is $60 \cdot 75.6 \cdot 10^{-6}$ or 0.004536. The total peak power requirement at 440 MHz is 19.7 MW and the average power requirement is 89.4 kW. A single Varian VA-812E klystron can satisfy both the peak and average power requirements of the 440-MHz portion of PIGMI.

The cavity power dissipation for the 1320 MHz portion of PIGMI is estimated to be 66.8 MW, and the beam loading for this same region corresponds to 14.6 MW. The cavity fill time of the 1320 MHz structure is only 3.6 μs, and the rf duty factor is 0.003816. The total peak power requirement at 1320 MHz is 81.4 MW and the average power requirement is 310.6 kW Five Litton L-5081 klystrons are capable of satisfying both the peak and average power requirements of the 1320 MHz portion of PIGMI. The PIGMI design is based on six such klystrons operating at a reduced level, providing the possibility, in emergencies, to continue operation in the event of the failure of a single klystron.

An appropriate PFN modulator has been designed and is being fabricated for the PIGMI component test program. Figure 22 shows a schematic diagram of the modulator and Fig. 23 shows the general physical properties of the 1320-MHz rf power system.

G. Computer Control and Instrumentation System

The PIGMI control and instrumentation system will provide the operator with a three-state control; namely, OFF, STANDBY, and ON. The STANDBY and ON states are identical in that all equipment is on and running within tolerance, with the exception that the beam is inhibited at the ion source and certain beam stops are inserted in the STANDBY state.

In either of these states, the operator can monitor the detailed performance of each and every system in the facility. All of the set-points designed to influence the performance of the machine are available to the operator through the control system. All of the these setpoints can be set up, monitored, and/or recorded for future set-up purposes by convenient parameter management procedures.

In the ON state, the operator can monitor the properties of the beam, the evidence of beam loss (if any), and the effects of beam loading on the accelerator equipment systems. Certain tuning procedures will be available to the operator for fine-tuning of the performance.

In the event of equipment failure, the control and diagnostic system will identify the faulty equipment and will notify the operator. In some cases, further diagnostics may be available to pinpoint the faulty unit in need of replacement. Most repairs will be accomplished by unit replacement.

All critical parameters will be monitored periodically and will be compared to their current setpoint values and tolerance limits. The operator will be notified of out-of-tolerance conditions, and in some cases, corrective action will be automated. Selected data will be collected on a regular basis for general and specialized logs to support machine records and statistical studies of machine performance.

The control system is comprised of a minicomputer, a control console, and a distributed array of small, modular, and intelligent control stations as shown in Fig. 24. The design is based on an advanced architecture developed and demonstrated at the Fermi National Accelerator Laboratory (FNAL). The design benefits from state-of-the-art engineering and from years of experience in controlling an operating linac. This general configuration will control several new accelerator facilities in the near future, including the injector linac of FNAL, the antiproton accumulator ring at FNAL, and the NBS/LASL racetrack microtron. The PIGMI system will benefit from these related applications.

The equipment systems under the surveillance of the control system include injector parameters, cavity field parameters, temperature control systems, forward and reflected powers, PFN modulator parameters, beam diagnostics, beam-spill radiation monitors, and a few electromagnetic quadrupoles and steering magnets. A few protection systems, such as the personnel safety system, the run-permit system, and the fast-protect system, are implemented independently of the control system, and provide their status, but no control, to the computer control system.

The control system will experience its heaviest load during commissioning, routine accelerator maintenance periods, and subsequent turn-on. These are also the periods in which the greatest demands will be made for good response from the system. The system will be expected to support accelerator maintenance with effective diagnostic testing and exercising of all subsystems. It will provide straightforward and, in some cases, automatic procedures for machine turn-on, tune-up, and fault recovery. Effective and responsive control will be provided at the operators console, including visual displays and timely execution of operator instructions. During the initial commissioning period and subsequent machine development periods, the control system will support a variety of beam diagnostic measurements.